Spectral and spatial uniformity in pushbroom imaging spectrometers

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ABSTRACT

Two simple and compact pushbroom spectrometer forms are described that can satisfy stringent spectral and spatial uniformity requirements in terms of minimizing distortion as well as the variation of the pixel spectral and spatial response functions.

Keywords: pushbroom imaging spectrometer, spectrometer design, spatial and spectral uniformity.

1. INTRODUCTION

It has been recently recognized that pushbroom imaging spectrometers must satisfy stringent spectral and spatial uniformity requirements in order to provide accurate spectroscopic and spatial information. These requirements go beyond the now commonly cited lack of distortion, to encompass the variation with field position in the shape of the spectral response function, and the variation with wavelength in the height of the optical point spread function.[1,2]

Extraction of accurate spectroscopic information depends on how well the spectral response function (SRF) of the various pixels is known. If, for the sake of simplicity, we accept that the SRF has a simple form that can be characterized by its peak location and halfwidth, then these two parameters must be known to within a small fraction (typ. 1-3%) of the nominal pixel bandwidth. And since, in a pushbroom system, one may have hundreds of thousands of pixels, it is preferable to ensure that those two parameters remain approximately constant, thus reducing dramatically the need for calibration of individual pixels or rows.

Pixels may contain mixed spectra for two reasons, either because there are materials with different spectral signatures in the same pixel, or because the optical point spread function (PSF) has a finite extent and thus causes light from one point on the ground to strike two or more pixels simultaneously. The second case is of concern because steps can be taken during optical design to facilitate spectral unmixing. Specifically, if all PSFs were of the same form, then algorithms could be developed that would take the PSF into account.[3] At the very least, an attempt should be made to minimize the PSF variation, or equivalently, minimize the variation of the spatial response function of the spectrometer.

We can understand the source of errors that cause nonuniformity with reference to figures 1 and 2. In Fig. 1, a schematic of an ideal spectrum produced by a pushbroom imaging spectrometer is shown. Since it is impossible to produce identical PSFs throughout wavelength and field, the PSF variation is constrained in the spectral and spatial directions individually. This ideal spectrum has the following characteristics: All image points are on the corners of perfect rectangles and aligned with the photodetector elements. The width of the PSF for any one wavelength is constant, independent of field. Also, the height of the PSF is constant, independent of wavelength and also independent of field.

Figure 2 shows a schematic of a realistic spectrum that contains the possible errors of optical origin in a pushbroom spectrometer. Along the 'B' column, the PSF centroids are not aligned; that is smile. The top spectrum is not aligned with a row, although the middle one is; that is keystone. The 'G' column shows variation in the width of the PSF with field location; this causes the width of the SRF of a pixel to vary with field, and produces an effect similar to that of smile. Finally, the bottom row shows a variation of the PSF height with wavelength; this variation has an effect similar to keystone.

Evidently, a spectrometer design should strive to satisfy the conditions of Fig. 1. Even if that is impossible, the spectrometer design should be assessed in terms of how closely it satisfies all those conditions, rather than merely in terms of distortion or encircled (ensquared) energy. The term 'spectrometer' should be understood here to include the entire optical design, since

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any front collection optic will in general modify the spectrometer PSF unless it can be made diffraction-limited throughout field and wavelength. However, for the sake of providing easy examples, the front optic is neglected in what follows.

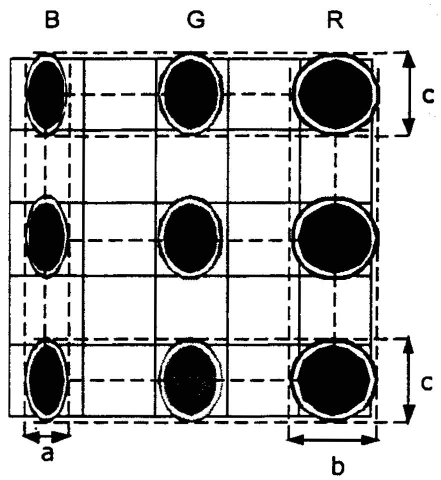

Figure 1: Schematic of an ideal spectrum produced by a pushbroom imaging spectrometer. The slit image is vertical and the spectrum of a field point is obtained horizontally, along the rows of the array. 'B', 'G', and 'R' stand for a hypothetical blue, green, and red part of the spectrum.

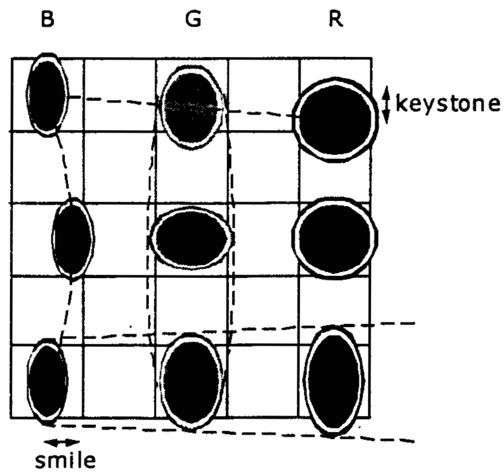

Figure 2: Schematic of the spectrum produced by a non-ideal pushbroom imaging spectrometer. In addition to geometric distortion, there is variation in the PSF width and height.

2. ACHIEVING SPECTRAL AND SPATIAL UNIFORMITY

The spectrometer designs that are capable of approximating the ideal performance of Fig. 1 are the concentric forms first described by Mertz.[4] If appropriately optimized, these forms can achieve distortion at the level of a small fraction of a pixel.[5] Typically this level of distortion correction is achieved at the expense of some image quality (or spot size), but the reduction of distortion is generally worthwhile. In order to improve the uniformity of response further, it will be generally necessary to degrade the PSF even more. Fortunately, such degradation can occur primarily for those fields and wavelengths where the PSF is better than needed. So in the end there is essentially no loss of image quality, in the sense that the energy ensquared in a pixel can be made to be greater than 80% throughout field and wavelength. In this respect, it should be understood that most of these errors would be reduced considerably if the pixels were made large. Unfortunately this is not always an option. Larger pixels mean a larger spectrometer and also probably a limitation in the number of pixels of IR arrays. The significance of the technique employed here is that it allows us to balance properly the performance of a spectrometer of the most compact size for the intended application.

Concentric spectrometer forms come in two flavors that are given the names 'Offner' and 'Dyson'. They both have a nominal magnification of -1 and are telecentric. In the original embodiment, the curved surfaces are concentric. A departure from that condition may be allowed, but it is advantageous to retain the centers on the same axis, for ease of alignment and testing.

A typical Offner design is shown in Fig. 3. This form is finding wide application in Earth and planetary remote sensing instruments,[6-10] although it is not clear whether those instruments have been designed for maximum uniformity of response or that they have taken full advantage of the inherent ability of the Offner design to provide such uniformity. From what indications one can gather from the literature, it would appear that the problem of uniformity has not been fully understood, and that although attention has been recently paid to reducing distortion, no actual pushbroom instrument exists that can meet the few percent level in both distortion and PSF variation as described above.

A typical Dyson spectrometer is shown in Fig. 4. Its main advantage is that it can handle low f-number beams, down to f/1. This form has not found as wide utility as the Offner. At least one instrument is reported to have used it,[11,12] although at a high f-number, which in part negates the speed advantage of the Dyson.

A brief comparison of the two forms is shown in Table 1.

Table 1

Comparison between Offner and Dyson concentric spectrometer forms

Offner		**Dyson**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
All reflective			Refractive interfaces create ghosts/scatter
Blazed gratings generally available (E-beam)[13]			Blazed gratings more difficult to procure
	Size increases rapidly with aperture, ~f/2 limit achieved with difficulty	Comfortably handles f-numbers down to f/1.	
Can achieve very low levels of distortion		Can achieve very low levels of distortion	
Can achieve high levels of spectral/spatial uniformity		Can achieve high levels of spectral/spatial uniformity	
Very compact		Very compact	
Typically amenable to a variety of packaging options			Proximity of object and image can cause severe packaging problems
	Relatively limited (spectral resolution) x (spectral range) product	Higher (spectral resolution) x (spectral range) product than Offner	
Typically no significant ghost problems			Ghost reflections from detector must be considered

The speed of the Dyson is of course a potential advantage but it also creates a difficult beamsplitting problem. At relatively high f-numbers, the problem is significantly ameliorated and one possible arrangement has been described by Lobb.[12] Also, the fast foreoptic required to take advantage of the Offner speed presents a difficult design and fabrication problem on its own.

3. SPECTROMETER EXAMPLES

Two spectrometer examples are shown below together with performance details. These examples have been specifically optimized for uniformity of response. Details of the optimization method will be reported separately. The first order parameters are shown in Table 2.

Table 2
First order parameters of two concentric spectrometers

	Offner	Dyson
Spectral range	1 – 2.5 μm	1 – 2.5 μm
Spectral sampling	10 nm	10 nm
Pixel size (square)	27 μm	18 μm
Slit length	19.44 mm	12.96 mm
No. of spatial pixels	720	720
f-number	4	1.3

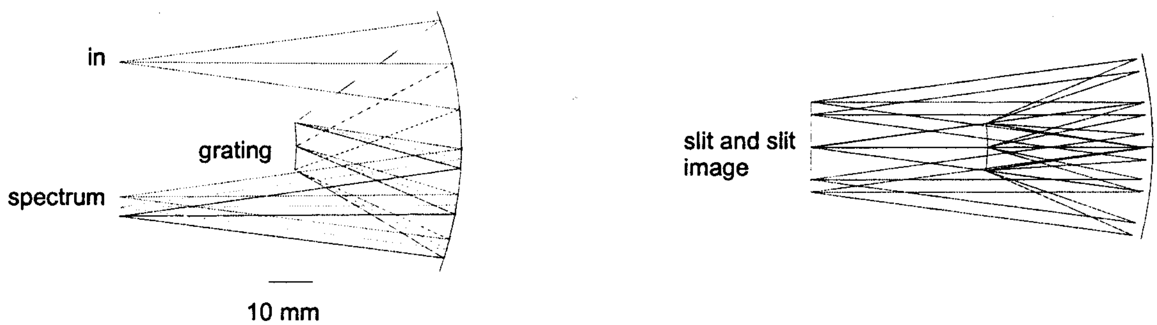

Figure 3: Offner grating spectrometer. Left: y-z view. Right: x-z view.

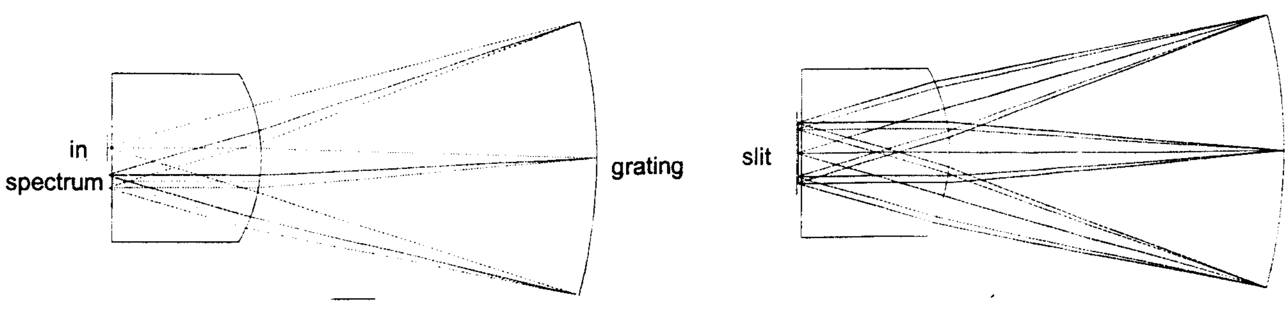

Figure 4. Dyson grating spectrometer. Left: y-z view. Right: x-z view. In this example, the image is formed in air but the object is at the input face of an extra small block of fused silica. A small prism can be used to fold the input beam up, if needed.

The performance of the spectrometers is assessed in terms of energy ensquared in the pixel, distortion (smile, keystone), as well as maximum variation in the spectral response function with field and also maximum variation in the spatial response function with wavelength and field. The spectral response function (SRF) of a pixel is computed as a double convolution of the input slit with the optical line spread function (LSF) in the spectral direction, and also with the pixel response. The slit and pixel responses are taken as simple rect functions. The spatial response function (SiRF) is computed as the convolution of the pixel with the optical LSF in the spatial direction.

Table 3 shows the some of the performance characteristics of the Offner spectrometer example of Fig. 3. The energy ensquared in a pixel is given for three wavelengths for the worst-case field location. Because of the relatively high f-number, even a perfect diffraction-limited spot is not fully contained within a pixel. Hence the absolute ensquared energy is also given as a fraction of the ensquared energy of the corresponding diffraction-limited spot at each wavelength. A pictorial representation of two worst-case PSFs is given in Fig. 5.

Table 3
Ensquared energy and distortion characteristics of the Offner spectrometer example

Ensquared energy in pixel (% of total PSF energy)			Ensquared energy in pixel (% of diffraction limited ensquared energy)			Smile*	Keystone*
1000 nm	1750 nm	2500 nm	1000 nm	1750 nm	2500 nm		
> 88	> 84	> 79	> 94	> 92	> 92	< 1%	< 2%

*: percent of pixel width

Figure 5: Worst-case PSFs for the Offner spectrometer example. Left: 1000 nm wavelength, right: 2500 nm wavelength. The size of the square is exactly one pixel (27 μm). The Strehl ratio for the long wavelength is 0.73.

Even though spot diagrams are inappropriate for nearly diffraction-limited systems, many people are accustomed to their use. Figure 6 shows the spot diagrams for the Offner example. This figure helps illustrate the point that the optimization method produced much worse spots in the short wavelength end than would be possible if the uniformity requirement was relaxed. Unless the optical designer understands clearly the need for uniformity, s/he would be tempted to reduce those spots further, gaining a little bit of spot size but ultimately ending up with a worse system.

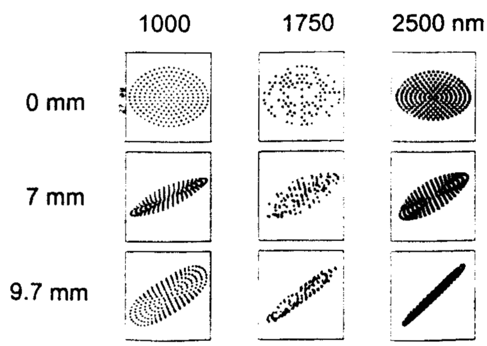

Figure 6: Spot diagrams for the Offner example (half slit). The system is symmetric about the center of the slit. Square size: 27 μm.

Finally, figures 7 and 8 show the maximum simulated variation in the SRF and the SiRF for any wavelength and field. The SRF comparison is done for all fields and one wavelength at a time. The SiRF comparison is first done for all wavelengths and one field point at a time, since this would be equivalent to a keystone error. The SiRF comparison as a function of field is harder because the SiRF is not fully independent of wavelength. However, the variation of the SiRF with field generally remains at the same level as the variation with wavelength.

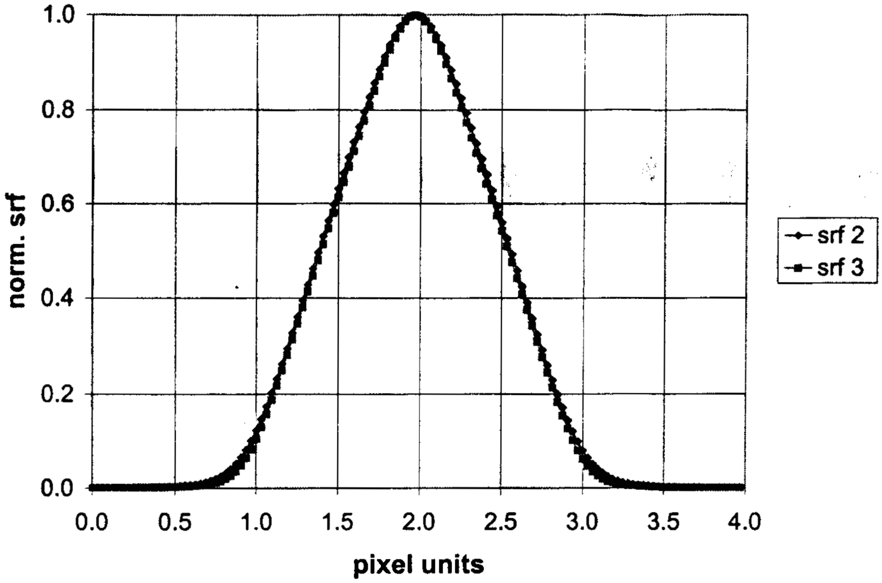

Figure 7: Maximum SRF variation for the Offner spectrometer example as a function of field, for any wavelength. The numbers '2' and '3' in the box refer to the field points at which the SRF was computed.

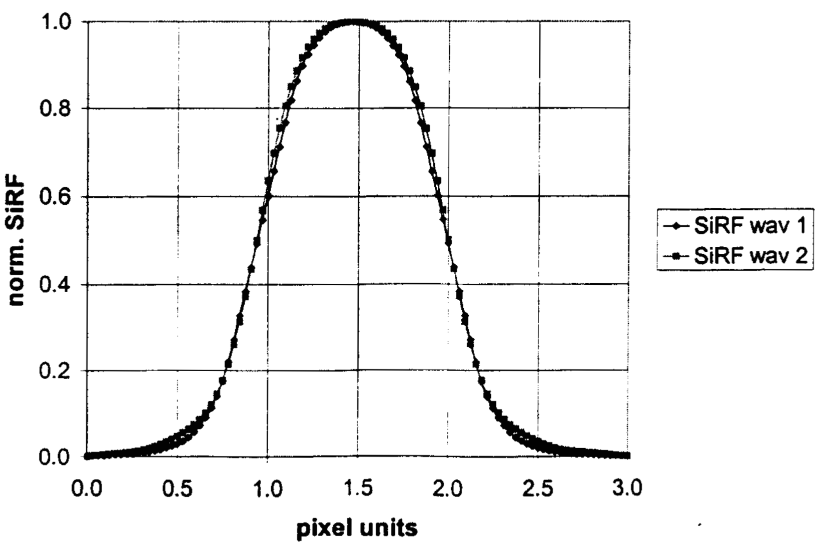

Figure 8: Maximum spatial response function variation for the Offner spectrometer as a function of wavelength, for any field.

We now consider the performance of the Dyson example. Table 4 shows the same performance measures for the Dyson as Table 3 did for the Offner, and Fig. 9 shows the worst-case PSFs for the short and long wavelengths.

Table 4
Ensquared energy and distortion characteristics of the Dyson spectrometer example

Ensquared energy in pixel (% of total PSF energy)			Ensquared energy in pixel (% of diffraction limited ensquared energy)			Smile*	Keystone*
1000 nm	1750 nm	2500 nm	1000 nm	1750 nm	2500 nm		
> 94	> 93	> 92	> 97	> 98	> 99	< 1%	< 1%

*: percent of pixel width

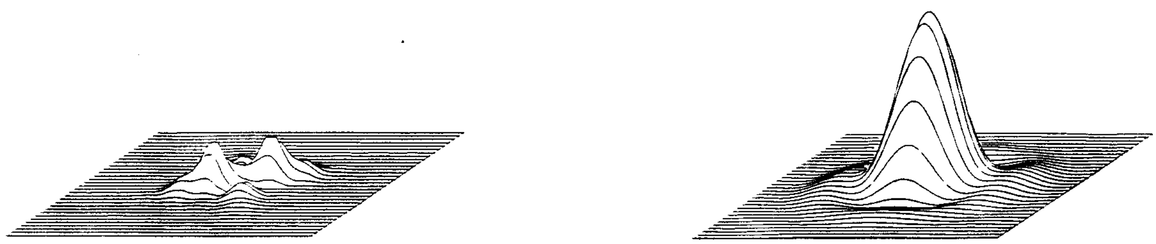

Figure 9: Worst-case PSFs for the Dyson spectrometer example. Left: 1000 nm wavelength, right: 2500 nm wavelength. The size of the square is exactly one pixel (18 μm). The Strehl ratio for the long wavelength is 0.85.

Figure 10 shows the spot diagrams for the Dyson system. The comment made earlier applies here, too: much better spots are possible if one sacrifices uniformity, but the optimum design is obtained by deliberately making the spots at the short wavelengths worse than they can be.

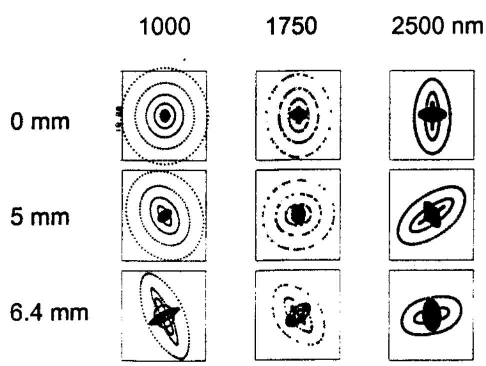

Figure 10: Spot diagrams for the Dyson example (half slit). The system is symmetric about the center of the slit. Square size: 18 μm.

The predicted SRF variation for the Dyson example is so small that it is difficult to display. It is shown in Fig. 11. The predicted SiRF variation is shown in Fig. 12. Although the SiRF variation has an effect similar to keystone, it cannot be converted to equivalent keystone in an immediately obvious way. However, the variation shown in both Fig. 8 and Fig. 12 is negligible.

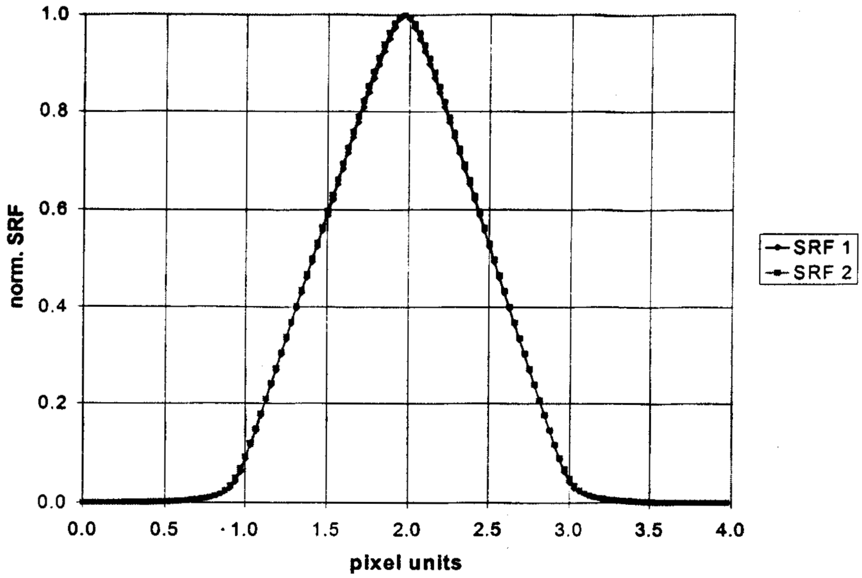

Figure 11: Maximum SRF variation for the Dyson spectrometer example.

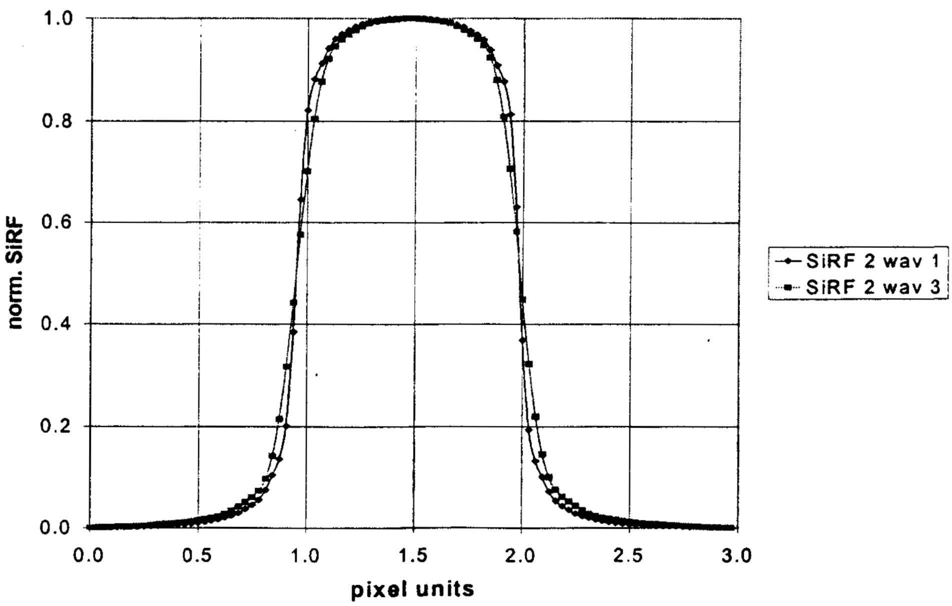

Figure 12: Maximum spatial response function variation for the Dyson spectrometer.

4. CONCLUSIONS

The need for a high degree of spatial and spectral response uniformity for a pushbroom spectrometer system has been discussed. The variation in the width and height of the PSF causes errors that are similar in nature to those caused by spectral and spatial distortion, and thus must be reduced to a level commensurate with the distortion in a spectrometer design. Two simple spectrometer forms have been presented that can be made to satisfy stringent spectral and spatial uniformity specifications while maintaining very simple construction with only spherical surfaces whose centers lie on a common axis.

The choice between the two forms must therefore be made on the basis of their other characteristics, the most important of which are the all-reflective nature of the Offner design against the high speed of the Dyson design.

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